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SEP 81 G T KAYE, G O PICKENS, T E STIXRUD
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Technical Report 738

REMOTE DRIFTING THERMISTOR ARRAY

A technique for observing internal waves in the upper ocean

GT Kaye
GO Pickens
TE Stixrud

September 1981

Research Report: October 1979 — September 1980

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A freely drifting vertical line array of thermistors was designed, constructed, and deployed to observe internal waves in the upper ocean. Thermal and pressure data were telemetered to a remote receiver. The array was effectively decoupled from the vertical motions of the sea surface and did provide useful internal wave measurements. The array is relatively inexpensive to construct and can be a useful device, especially when used in conjunction with observations from an accompanying ship, for internal wave survey operations.

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INTRODUCTION

The remote drifting thermistor array is a demonstration of a simple, inexpensive data collection system for sampling physical oceanographic phenomena in near-surface waters. It has been difficult in past research efforts to make meaningful measurements near the sea surface because of data contamination due to sensor motion. For measurements from ships, this sensor motion is induced by both ship drift and vertical heaving due to surface gravity waves. For measurements with bottom-moored instrumentation, sensor motion is due to mooring wander, since the mooring in deep water cannot be sufficiently constrained to prevent the waving of shallow sensors at its top. A method to avoid this contamination has been provided by developments in sonobuoy technology. By adding a sea anchor, inserting a compliant suspension cable, and distributing buoyancy appropriately, the motion of the surface float, which follows the surface waves, is decoupled from the sensor array. Thus the sensors remain nearly motionless and the sampled data can be telemetered by a transmitter on the surface float to a nearby ship, to a satellite, or even directly to a shore-based receiver.

We have used this engineering concept to instrument a vertical array with temperature sensors in order to observe internal waves in the upper 250 m of the ocean water column. Future work will be concerned with demonstrating that an upper-ocean internal wave antenna can be constructed with several of these drifting arrays.

Equally important is the demonstration that upper-ocean measurements can be made confidently and remotely with a simple, easily deployed system. This drifting array technique allows numerous types of measurements to be made from a single surface platform. These measurements can complement the data that are telemetered from the drifting array to the ship. Some of the types of sensors that could be used in this array are thermistors, hydrophones, conductivity cells, current meters, chemical detectors, optical receivers, and magnetic and electric field sensors. Thus the technology demonstrated by this work has immediate potential for the entire oceanographic community in understanding the complicated environment of the upper ocean.

APPLICATION TO INTERNAL WAVES

The first useful measurements of internal waves were made by Kalle (Ref 1) from a drifting ship in the Baltic Sea. Observations were made with four temperature-sensing elements that were suspended at a depth of 28 m from four parts of the ship. LaFond (Ref 2) greatly improved this technology with measurements from a tower near San Diego, when he developed a three-point array which tracked the depth fluctuations of isotherms. The main disadvantage of the technique was that the measurements were made in shallow water and the observed wave fields were atypical of deep-water conditions. This was overcome with the development of temperature—depth profilers that were operated in deep water from the research platform FLIP by Zalkan (Ref 3) and Pinkel (Ref 4). By using three spaced profilers, Pinkel investigated not only the frequency content of the wave field, but also observed some of the wave number content. His understanding of wave number energy distribution and directionality was limited by the small horizontal aperture of his array. In continuing work (Ref 5) Pinkel has developed high-frequency acoustic doppler velocimeters as remote sensors of the water velocity field and increased the aperture of his measurements to over a kilometer horizontally. The disadvantage of this sophisticated technique is that it is tied to a non-self-propelled platform, so that large-scale geographic measurements with the technique are expensive and impractical.

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1. K. Kalle, "Uber die innere thermische Unruhe des Meeres," Ann. d. Hydr. u. Marit., Meteorol., 70, 1942, 383.
2. E. C. LaFond, "The Isotherm Follower," J. Mar. Res., 19(1), 1961, 33-39.
3. R. L. Zalkan, "High frequency Internal Waves in the Pacific Ocean," Deep-Sea Res., 17, 1971, 91-108.
4. R. Pinkel, "Upper Ocean Internal Wave Observations from Flip," J. Geophys. Res., 80(3), 1975, 3892-3910.
5. R. Pinkel, The use of Acoustic Doppler Sonar for Upper Ocean Velocity Measurements, Marine Physical Laboratory Report MPL-U-86/77. Scripps Institution of Oceanography, 1977.

Another technique for measuring upper-ocean internal waves is to tow a vertical array of sensors. These sensors estimate water vertical displacements and thus measure the horizontal wavelengths of the motions (see, for example, Ref 6). The main disadvantage of the towed array is that one measures only a component of the internal wavelength, since we do not know the direction of propagation for any individual cycle. If one tows in a geometrical pattern, one can estimate the total energy by wavelength in the tow direction and acquire an indication of the anisotropy by comparing the results of different tow directions. Unfortunately the wave field can vary temporally while one is attempting to determine the spatial characteristics.

The remote drifting array represents an additional tool that can fit easily into the sampling pattern of the towed array. It provides a measurement of the frequency content of the field, while the towed array determines the wavelength content. This information plus supporting measurements of the current shear and the vertical density profile provides sufficient information to describe the upper-ocean internal wave activity at that position and at that time. The portability and deployment ease of the drifting array make it an ideal tool for large-scale geographic measurements for either scientific or survey operations.

DESIRED ARRAY CHARACTERISTICS

In order for the array to have characteristics useful for both scientific and survey operations, it should be:

1. Relatively inexpensive so that it can be replaced if lost or damaged

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6. E. J. Katz, "Tow Spectra from MODE," J. Geophys. Res., 80(3), 1975, 1163-1167.

2. Portable and small in volume so that storage requirements are minimal

3. Easily deployed in mild to moderate sea states

4. Of simple design for easy maintenance and operation by a variety of scientists and technicians

5. Able to transmit data reliably

6. Decoupled from sea surface motions and unresponsive to heaving due to internal waves

7. Sensitive and accurate in the measurement of temperature fluctuations from which the internal wave displacements will be inferred.

These characteristics will be described during the course of the system description.

MECHANICAL SYSTEM DESCRIPTION

Total funds for the system development were $45K; we estimate that it can be duplicated for $15K. The in-air weight of the components is 150 lb (68 kg) and the in-water weight is 65 lb (29.5 kg). The array is coiled in a wooden crate whose outside dimensions are 3 x 3 x 1 1/2 ft. Additional storage is required for a surface float and a drogue.

A fully assembled array is shown in Fig 1. A description of the array components, numbered as in Fig 1, is as follows:

1. This is a simple marker buoy with a flag for aiding in the visual identification of the array at sea.

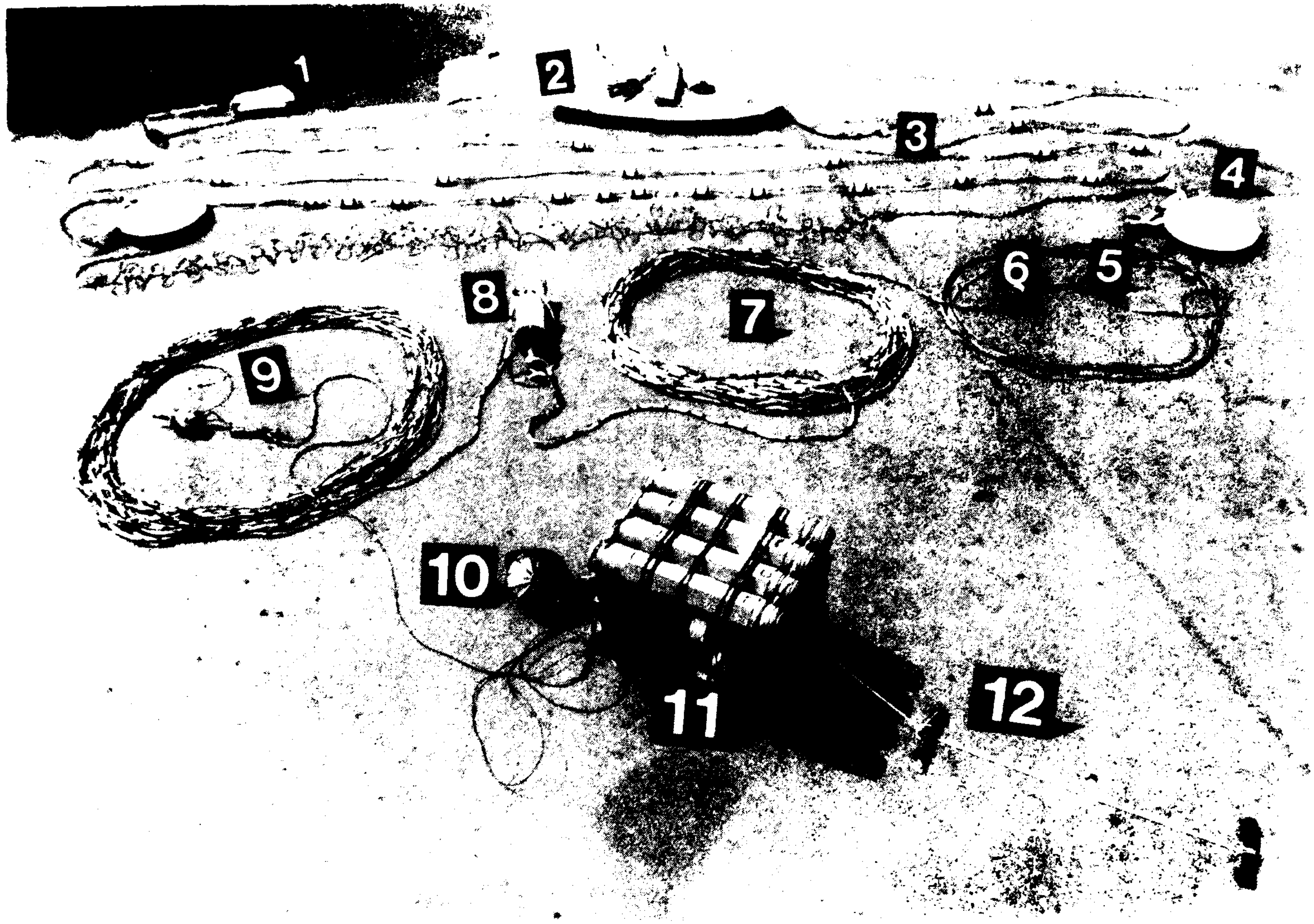

Figure 1. Assembled Thermistor Array.

2. The transmitter float is a short surfboard with three sonobuoy transmitters and a composite of dry cells and seawater batteries, which are paralleled through diodes so that failure of one voltage source will not drain the others. One transmitter is used for the thermal array, while the other two were dedicated to acoustic channels. It is practical to multiplex all three data sources for transmission over one radio channel.

3. Twenty-two floats were fastened along the support cables at 1/2-m intervals. Some of these lay on the surface, while others were pulled under by the net weight of the array. The remaining floats are continually surfacing and submerging as a consequence of surface waves and swell. Since each float has a buoyancy of only 0.4 kg, submergence of these floats by surface waves does not cause abrupt heaving actions on the support cable that leads to the array. The floats were fashioned from a fine-grained styrofoam material, which shrinks only 5% in volume for a pressure increase of 110 psi (about 75 m of water depth).

4. These two streamlined floats, each with a buoyancy of 26 lb (12 kg), serve as the main buoyancy units for the array. When not under tension, the units are spaced 10 m apart. A compliant member of standard surgical tubing is fastened around a length of Kevlar line. Tensions of less than 100 lb are taken up by the surgical tubing, while tensions greater than this are handled by the Kevlar line. In addition to the small-float arrangement, the surgical tubing acts as an analog filter, removing or damping the effects of surface waves.

5. A pressure gauge was placed at 40 m depth to monitor the apparent depth fluctuation of the upper end of the array. This is a Bourne pressure gauge with a range of 75 psi, a sensitivity of 15 cm in depth variation, and an accuracy of 40 cm in absolute depth. The time constant is unknown; however, this instrument has been used by some of the authors in past research to measure surface gravity waves.

6. This hydrophone was fabricated at NOSC and used as a secondary sensor to monitor array motions through acoustic noise intensity fluctuations.

7. The upper half of the array consists of ten thermistor pairs, all Fenwall thermistors, whose characteristics were matched for response agreement. These characteristics are a sensitivity of about 0.005 C°, an accuracy of 0.01 C° and a time constant of 400 ms.

8. The electronics sampling canister was positioned in the array center and provided termination for 20 thermistor pairs, 2 pressure gauges, and 2 twisted pairs from the canister to the main surface float for data transmission. The thermistors were all sampled instantaneously, once every 2 s, and their digitized output was telemetered in series during most of the remainder of the 2-s sampling interval. This is described in greater detail in the Electronics System Description below.

9. The lower half of the array also consisted of 10 thermistor pairs, stationed at 10-m intervals from depths of 140 to 230 m. Immediately below the deepest thermistor pair is another hydrophone and a Bourne pressure gauge. This had a pressure range of 0-500 psi (about 340 m of water depth).

10. This is a glass-ball float in a protective case, the combination having a net positive buoyancy of 5.5 kg. Its purpose was to help raise the lower end of the array when the terminal weights were dropped.

11. The array drogue was fashioned from empty sonobuoy cases and coupled the array to the horizontal motions of the upper water current. By moving with the current, the doppler shifting of the internal waves which would be encountered if the array were fixed with respect to the bottom is minimized. Additionally, the 16 sonobuoy cases entrap a water mass of 1030 lb (467 kg), and provide drag so as to minimize vertical heaving of the entire system.

12. The terminal weights had a net negative buoyancy of 5.5 kg. During recovery, a weak link is sheared and these weights are released. This results in a net positive buoyancy of the end of the array so that the end rises to the surface and aids in easy recovery from the ship.

The array is handled without difficulty by three or four people from a small torpedo retriever boat in sea states 0 to 3. A davit or light crane is

useful in handling. The deployment and recovery sequences require around 30-45 min each. The boat can be drifting, with the array being paid out to windward away from the boat drift. In higher sea states the boat should be headed slowly into the seas while the array is paid out downsea. The deployment sequence starts with the top of the array by launching the surface transmitter float, the upper half of the array, the electronics sampling canister, the lower half of the array, the drogue, and finally the terminal weights. After releasing the system from the platform, the array requires about 10 min to attain a vertical orientation and approximately 20 min to reach equilibrium.

The recovery sequence is similar. The surface transmitter float is brought aboard and secured. The boat is moved slowly ahead to generate a light tension in the support cable, which shears a weak link and drops the terminal weights. The boat is then backed down slowly while the upper half of the array is recovered. During this time the lower end of the array has acquired a net positive buoyancy due to the loss of the terminal weights and is rising slowly to the surface. First the electronics canister is recovered and then the lower half of the array. The most difficult part of recovery is bringing aboard the drogue of sonobuoy cases, which though light, is bulky. The choice of sonobuoy cases for the drogue was one of convenience; improvement is possible with a design similar to a current cross.

ELECTRONICS SYSTEM DESCRIPTION

The major part of the electronics is contained in the sampling canister, which is stationed at the array center. A pair of wires from each of the 20 pairs of thermistors and from the 2 pressure gauges enter the canister to join the appropriate circuits. Also, wire pairs from each of the two hydrophones enter the canister and immediately exit on conductors leading to their respective transmitters on the surface float. An 18-V nickel-cadmium battery within the canister supplies the power for a 30-hour operation. This operational lifetime can be increased. The battery is turned on by means of a

mercury switch whenever the canister is in an upright position. Consequently the canister is stored in an upside-down condition and righted just before deployment.

The method that we have used for determining the thermistor bead resistances is either unique or so rarely used as to have escaped our attention. The normal method is to send a very small current through each bead so as not to cause a significant temperature rise. The small voltages resulting from temperature variations required considerable amplification, with the attendant risk of errors due to contact voltages and drifts in gain and bias. Occasionally higher currents have been used and the added induced temperatures of the beads have been factored from the results. This often cannot be done with the necessary precision, because the electrically induced temperature rises in the beads have a variable dependence on conduction to the surrounding water. For example, water of constant temperature which is moving rapidly over the surface of the bead or its housing tends to cool a bead below its normal electrically elevated temperature. In the present implementation, high electrical currents are used, but the measurements are made *before* the beads have had time to respond. All 20 beads are strobed in unison with the high current of nearly 1 mA each. The strobing current lasts only 1.5 ms. During the middle 0.5 ms of the strobe, the analog voltage from each bead is sampled, amplified by a factor of four, and stored in a capacitor. Voltages from all of these capacitors, plus additional readings, are serially digitized and telemetered between sampling times.

Each of the 20 temperature measurements and the 2 depth indications are converted into a 12-bit binary word. Each word follows a fixed "0" bit and progresses through its 9 least significant bits. Next comes the fixed bits of "100", followed by the 3 remaining bits, with the most significant last. Following each of these words is a fixed string of "1111." This forms a composite word having a total of 20 bits. In the same manner two "housekeeping" measurements are also included. These are presently the terminal voltage of the associated battery and the voltage following the voltage regulator. The resulting 24 words together with their fixed bit patterns result in 24 X 20 or 480 bits for each measurement cycle. At 2 s/cycle and 250 bits/s, the 480 bits fall 32 bits short of completing the available 512. These excess bits

are turned into 32 consecutive 1's to clearly mark the beginning and end of each frame (or measurement cycle). Thus, both individual words and frames are clearly set off by the fixed patterns of bits.

Just prior to transmission, this bit stream undergoes a translation from simple binary to a "split-phase" representation. This removes the dc and low-frequency ac content of the voltage variations associated with the serial data string and thereby allows the use of capacitive coupling in the amplifiers and the employment of an analog recorder. After this translation, each "1" becomes a "10" and each "0" becomes a "01", resulting in a transmitted bit rate of 512/s, as can be seen in Fig 2a. Figure 2b shows a sample datum as it is coded and telemetered.

In the present implementation, these data are recorded on an analog (also called "direct") recorder. The tape of the analog recorder is transcribed to a digital tape format prior to computer processing.

The two hydrophone channels occupy two additional tracks on the analog recorder.

Although 12 bits were available for data representation, the accuracies required for this demonstration used only 8 significant bits. Sensors which require more than 12-bit accuracies can be handled by the present design with minor electronics modifications. For the 22 hours of recorded data from two deployments, the sampling system functioned very well, with only minor data losses. The only malfunction was the infrequent addition of an extra bit to a datum. Since our data were recorded in analog form and digitized subsequent to the field tests, this added bit, which was not significant, was detected and removed in the digitization software. This problem has since been corrected.

Data were recorded from a ship-based receiver at ranges of up to 5 nmi. Greater ranges, up to 15 nmi, were obtained with a shore-based receiver when it was placed at a higher elevation (on San Clemente Island). The transmission frequency was a standard VLF sonobuoy frequency, a regime which limits the reception range to line-of-sight distances. For operational uses, we

Figure 2a. "Split-phase" representations for digital bits of "1" (left) and "0" (right).

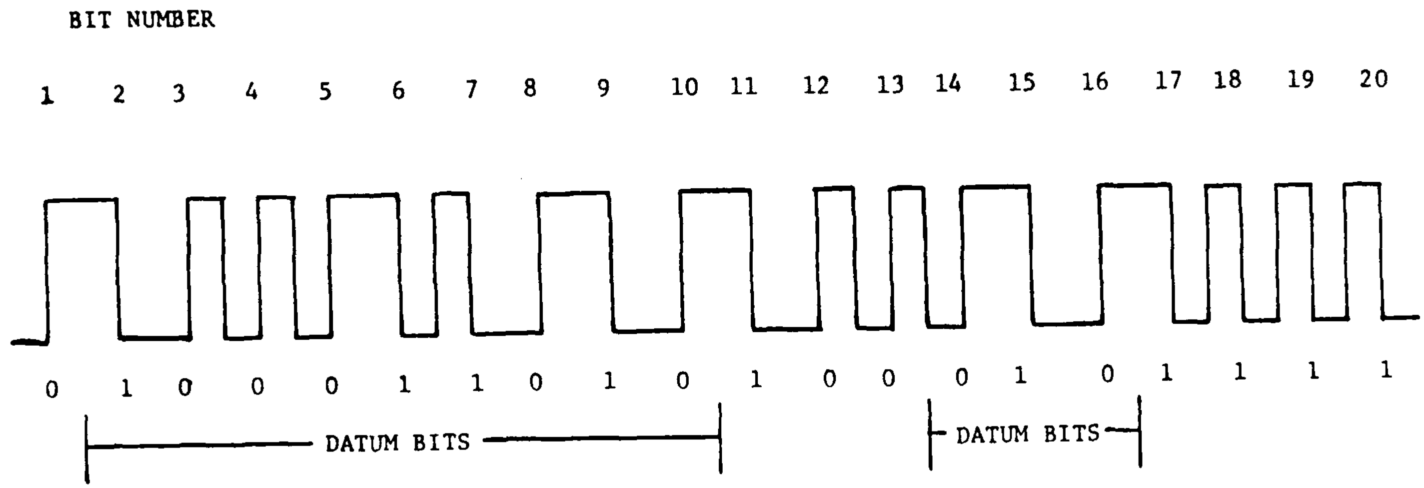

Figure 2b. Sample datum as it is telemetered in split-phase representation. Bits 2-10 and 14-16 are the datum, with bit 2 as the least significant bit and bit 16 the most significant.

anticipate no difficulties in shifting the transmission frequency down to the HF band in order to expand the reception range significantly.

FIELD TESTING

The array has been deployed twice. The first, a test of the engineering design, took place on 1 August 1980 at a position 5 nmi northwest of San Diego Harbor in 400 m of water. The deployment, which went smoothly, was in sea state one conditions and recovery was in sea state two. This test showed that the buoyancy floats had been distributed properly, that the array performed as designed, and that temperature information was transmitted and recorded.

The second test was conducted on 27-28 August 1980 at a position immediately west of San Clemente Island in 400 m of water. Deployment and recovery from a torpedo retriever boat were accomplished in sea state three conditions. Shortly after deployment the terminal weights were lost from the bottom of the array. This caused the lower half of the array to become positively buoyant and rise. Temperature information from the lower half was discarded during the data analysis.

The deployment position was 3 nmi due west of the island. The bearing to the drifting array was tracked with a shore-based directional antenna. During the afternoon of the 27th, the array was advected southward with the surface current. During the night the current reversed direction, and the array was advected northward. It was recovered on the 28th at a position 5 nmi northwest of its deployment site. This capability to move with the surface current demonstrates the advantage of a drifting array over moored devices. The internal wave field is also advected with the current, so that a moored sensor observes an unknown doppler shift in the waves. This in turn produces a variation in energy density level in the frequency domain. By using an array which moves with the current, this doppler shifting is minimized and more accurate measurements of wave frequency are made.

ARRAY MOTION RESPONSE

Our first concern in the data analysis was to demonstrate that the array was effectively decoupled from the sea surface. If the array were to heave vertically in response to surface waves, future operations would have required a high data sampling rate and subsequent low-pass filtering of the time series in an attempt to remove the surface wave contamination. This would seriously degrade the sensitivity of the internal wave measurements. To test this concern, we plotted the time series of the pressure gauge output and performed a time series analysis of the data.

Figure 3 is the time series of the shallow pressure sensor for an initial time 30 min after deployment. The total depth variation over the 20-hour record is 4 m. Because of the inadvertent loss of the terminal weights, the array was significantly less resistant to vertical heave than it would have been with the added negative buoyancy provided by the weights.

Figure 4 is an energy density spectrum of this time series. The surface wave band occupies a frequency regime around 180-1200 cycles per hour (cph). The spectrum is nearly flat in this regime, with energy density values at the noise level of the pressure gauge of 7.5 cm rms. For comparison, an energy level for a 1-m-amplitude surface wave (around 6 ft crest to trough), which would be expected in sea state 2-3, is indicated in Figure 4 also. From this we conclude that there was no measurable response of the array to sea surface motions and that the array is effectively decoupled from the sea surface.

A second aspect of Fig 4 is the array motion at internal wave frequencies, which extend from the low-frequency end of the spectrum at 0.22 cph up to around 9 cph. Here the energy density spectrum of the pressure gauge output is not flat, which indicates that the array was heaving at internal wave frequencies. This response is aproximated by an f^{-1} power law, and a sample line is drawn through the spectrum at these frequencies to show this. Also plotted is an f^{-2} power law line, which one would expect for the internal wave field. This line was drawn in accordance with the GM75 internal wave model

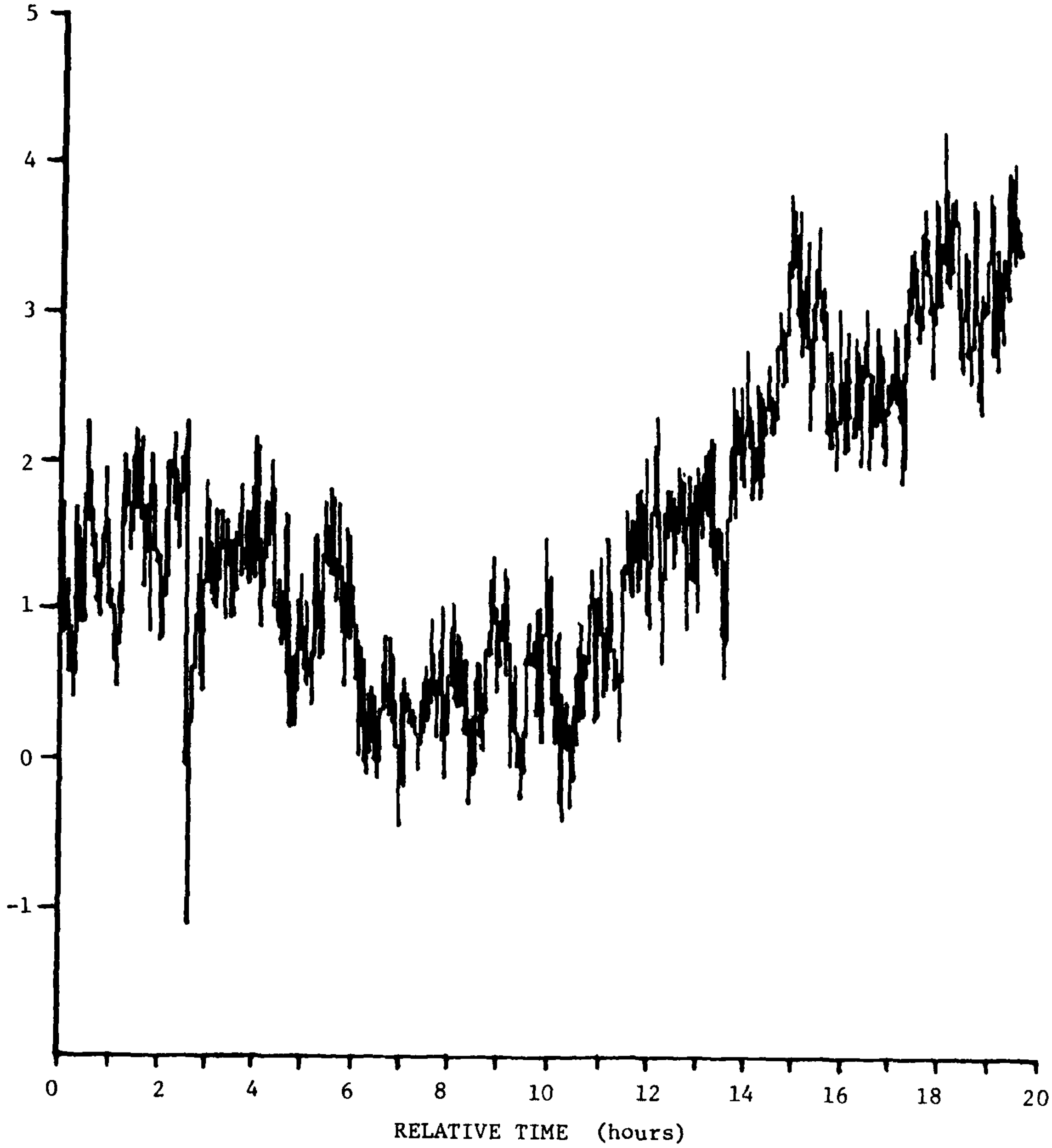

Figure 3. Array depth fluctuation time series inferred from shallow pressure output. This series began 30 min after array deployment.

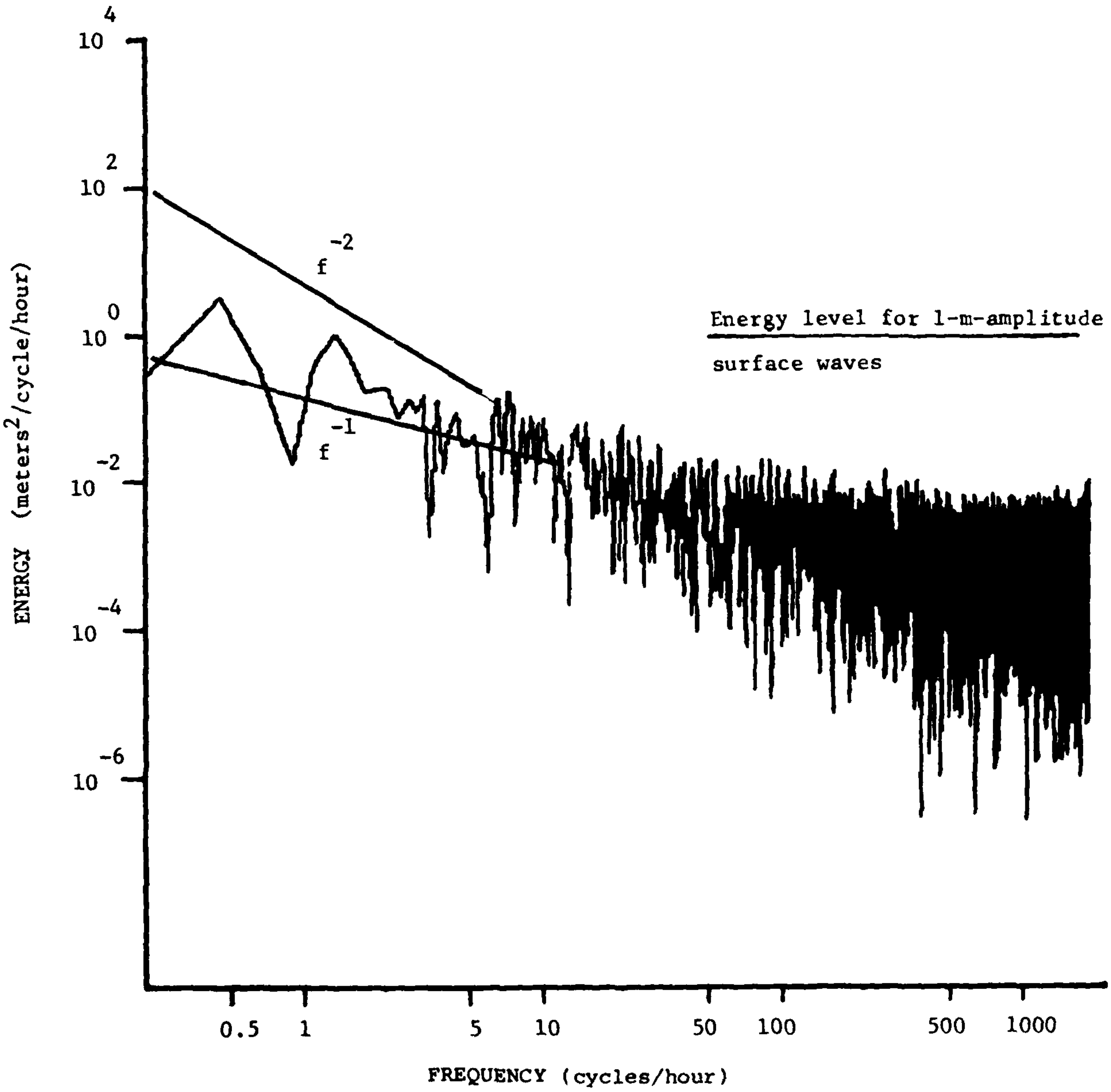

Figure 4. Energy density spectrum of array vertical motion as sensed by the shallow pressure sensor.

(Ref 7). Although the array did respond somewhat to the internal wave field, this response is small. At the lower frequencies, only 10% of the motion that we would expect if the array were moving exactly with internal waves is seen. At the higher frequencies, the array responded with an amplitude of about one-third of the wave field. This response is much greater than that for which the array was designed. We feel that this was due to the loss of the terminal weights, which effectively removed the dashpot from the spring-mass system. We expect that future deployments will demonstrate that the array does not heave vertically in response to internal wave frequencies.

DATA ANALYSIS

A time series plot of temperature fluctuations that were observed with the ten thermistors of the upper half of the array is shown in Fig 5. We have normalized each time series to the maximum range of temperature variation that was observed at each individual sensor. The total range is marked on the left-hand side of the plot and indicates that the thermistors at depths of 60, 70, 80, and 90 m were in relatively weak vertical temperature gradients, so that temperature excursions were less than 1/2 C° over the 20-hour period of data recording. The prominent feature of this figure is the tidal oscillation, which is seen at all depths and has a period of about 12 hours.

Energy density spectra of temperature fluctuations were computed for these ten thermistors. All spectra have similar features, and three examples are shown in Fig 6-8 for sensor depths of 40, 60, and 80 m, respectively. For wave frequencies of 0.22 to about 9 cph, the slopes are well represented by an f^{-2} energy spectrum, as can be seen by the lines drawn for comparison within this frequency regime. Above 9 cph the data fall off more steeply according to f^{-3} or perhaps f^{-4}. This agrees with the GM75 model and the observations of Pinkel (Ref 4). Of special note is the "hump" in Fig 7 near the Vaisala

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7. C. Garrett and W. Munk, "Space-time Scales of Internal Waves: a progress report," J. Geophys. Res., 80(3), 1975, 291-297.

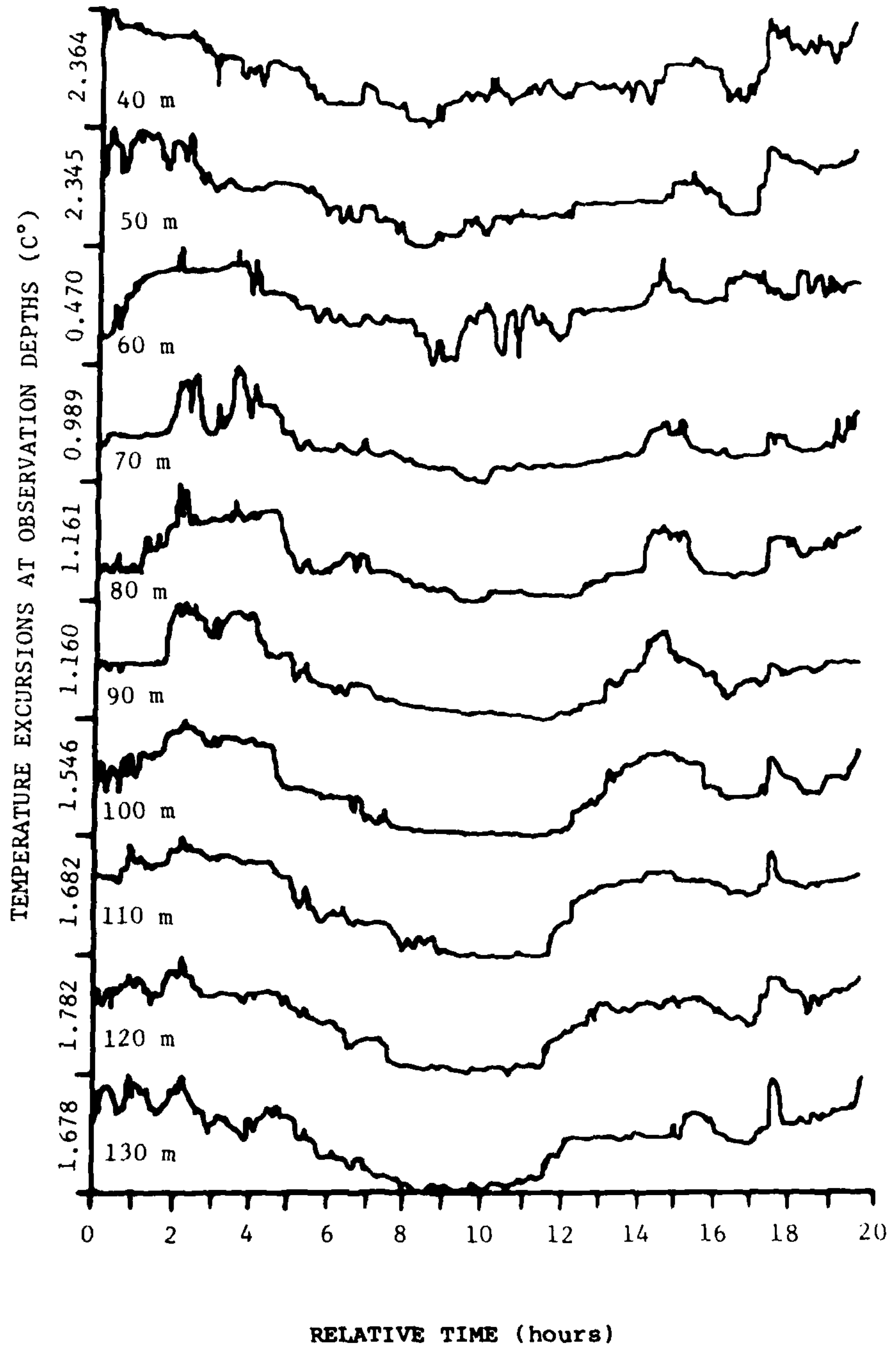

Figure 5. Time series of temperature fluctuations at observation depths.

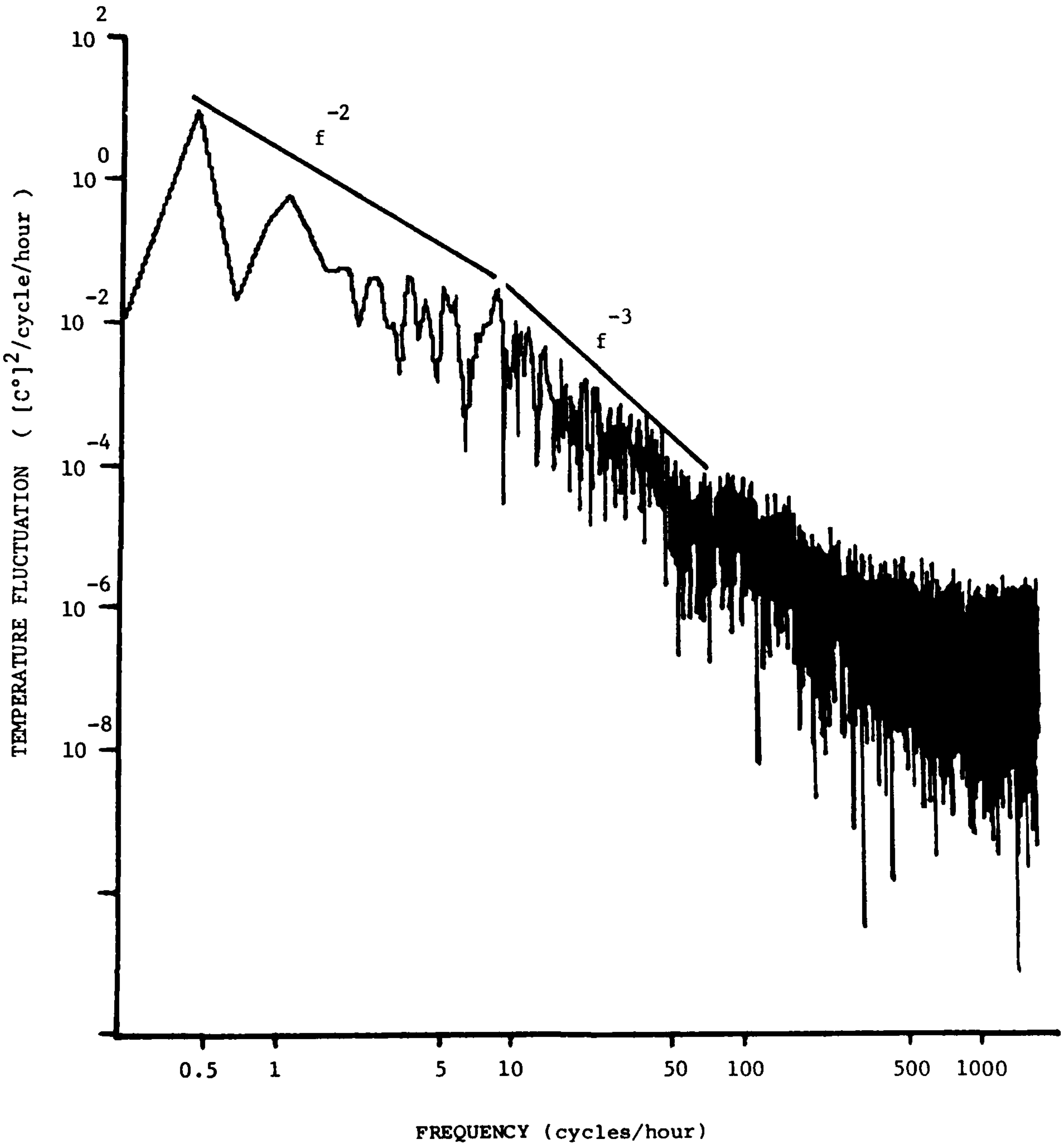

Figure 6. Energy density spectrum of temperature fluctuations observed at 40 m depth.

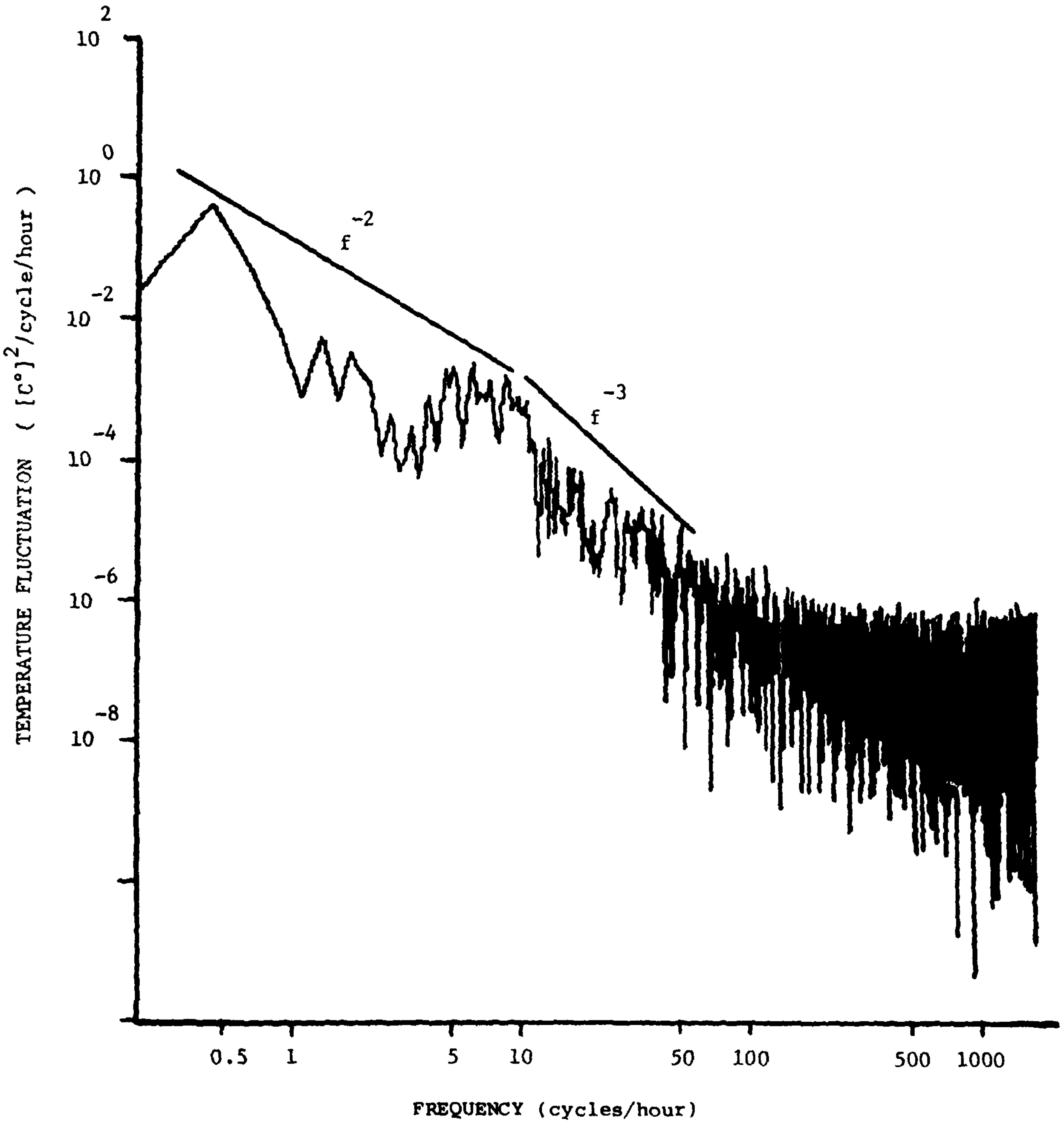

Figure 7. Energy density spectrum of temperature fluctuations observed at 60 m depth.

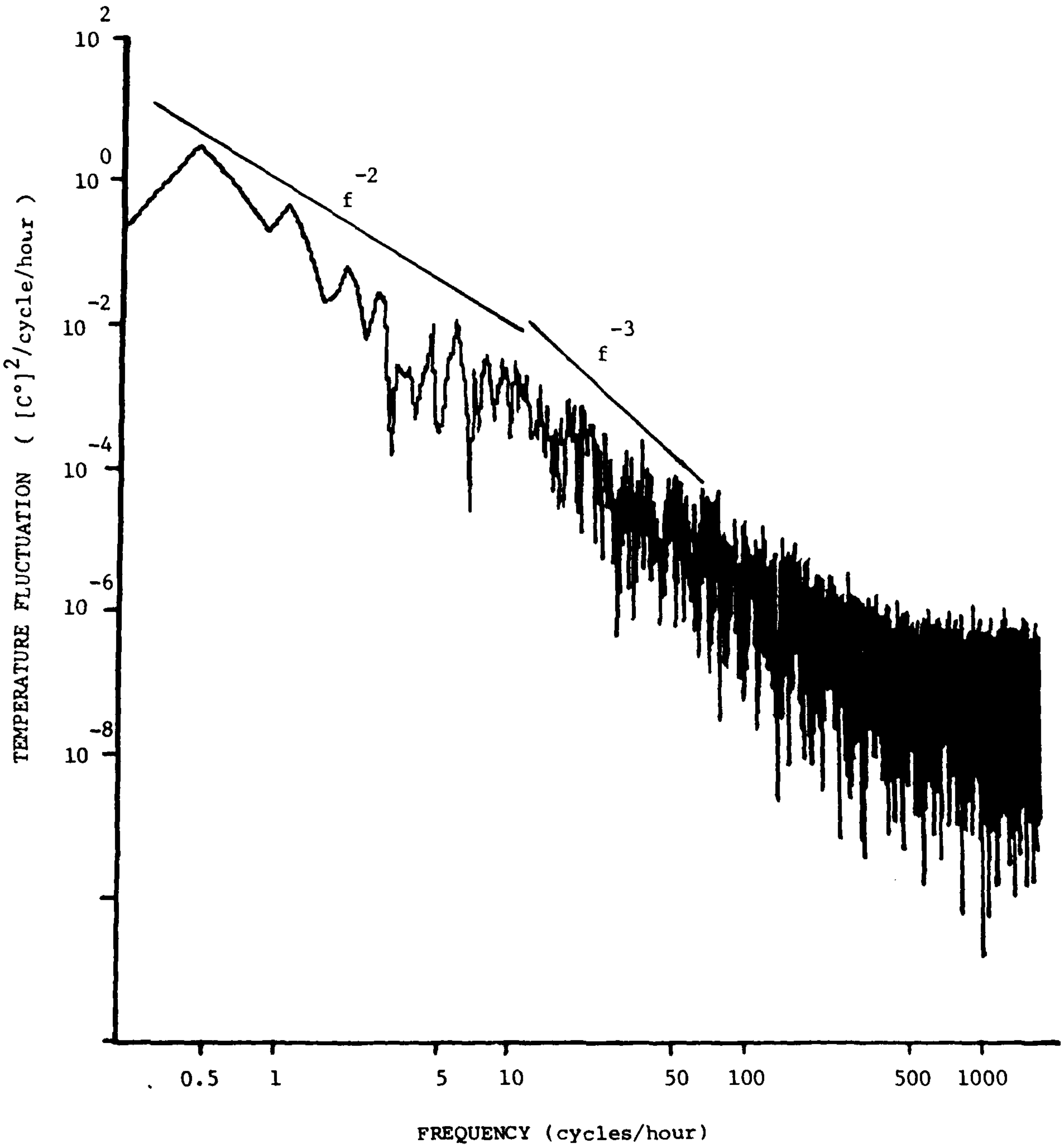

Figure 8. Energy density spectrum of temperature fluctuations observed at 80 m depth.

frequency of 9 cph. This variation from the f^{-2} spectrum has been observed in the upper ocean by Pinkel and others, but the reason for this energy deviation is not presently understood.

A plot of the average of the ten thermistor spectra is shown in Fig 9. For the internal wave frequency regime below 9 cph, the spectrum is well approximated by the f^{-2} spectrum. The Vaisala frequency is a function of depth and the stratification local to the sensor. Averaging the spectra at ten different depths in the thermocline has a tendency to muddle the identification of this frequency and to modify the rapid falloff above this frequency. In spite of this averaging, the spectrum falls off at least as rapidly as $f^{-2.5}$ and perhaps faster. Note that there is a change in the ordinate. The spectra fall off to a noise floor near 200 cph, and there is no apparent energy detected at surface wave frequencies, as would be expected from the pressure gauge data analysis. This noise floor is around 40 dB in power below the internal wave high-frequency cutoff at the Vaisala frequency.

We conclude that the thermistor array has performed well as a system for upper-ocean observations. It provided useful internal wave measurements, especially at high frequencies, without being contaminated by surface wave motions.

CONCLUSIONS

1. A drifting vertical thermistor array was constructed that sampled oceanic temperature fluctuations at 20 depth intervals over a 190-m vertical aperture in the upper ocean.

2. The array is portable and capable of being deployed off small boats in sea states of 0-3. Temperature and depth information is sampled and telemetered to a remote receiver. Data record lengths of several days are possible with the present battery configuration.

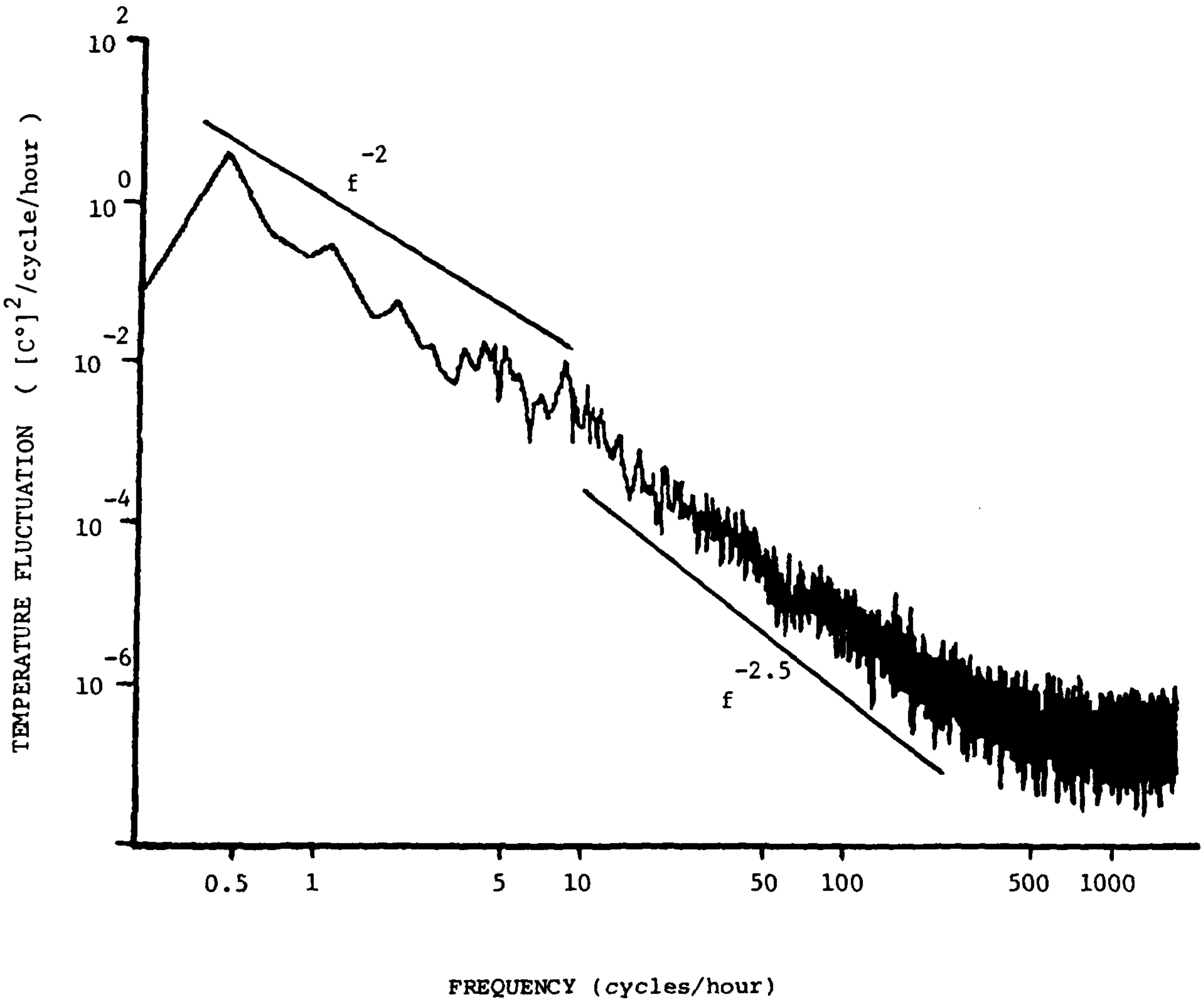

Figure 9. Averaged energy density spectrum of temperature fluctuations observed at ten sensors in upper half of the array.

3. The array is effectively decoupled from sea surface motions by its design. Due to an equipment failure there was some vertical heaving of the array at internal wave frequencies. It is expected that proper deployment of the array will eliminate this response.

4. Temperature information was sampled at a 0.5-Hz rate with very low data loss. Internal waves were observed. Energy density spectra of the temperature fluctuations revealed an f^{-2} falloff within the internal wave band as would be expected. Above the Vaisala frequency, a rapid falloff in energy was observed. In some sensors an increase in energy at frequencies near Vaisala was observed.

5. For initial tests, the array performed well and can be expected to be an excellent survey tool for upper ocean internal waves at minimal cost. Used in conjunction with a surface platform that provides additional measurements (eg, density profiles, shear profiles, temperature profiles from towed thermistor chains), the array will be a useful survey device for studying internal wave motions over wide geographic areas.

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